CROWDTHERMAL DELIVERABLE D1.2

SYNTHESIS OF ENVIRONMENTAL FACTORS

Summary:

This report presents a state-of-the-art literature review of environmental factors influencing public support of geothermal energy projects. Environmental factors throughout the different lifecycle phases of deep and shallow geothermal energy projects are investigated. Relevant project phases as adopted by the CROWDTHERMAL consortium are divided into: project definition, exploration, drilling, construction, operation and decommissioning & post-closure. Environmental impacts are classified in terms of environmental matrices: air impacts, water impacts, land impacts, and others (noise & visual pollution and radioactivity).

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1 EXECUTIVE SUMMARY

This report focuses on reviewing environmental factors affecting the public acceptance of geothermal energy projects.

The environmental factors are classified in terms of environmental matrices, namely:

- Air impacts, including emissions to the atmosphere
- Water impacts, including water pollution and water consumption
- Land impacts, including induced seismicity, land subsidence, land use and solid waste
- Noise & visual pollution and radioactivity

The environmental factors are analysed in relation to the geothermal project phases adopted by the CROWDTHERMAL consortium:

- Project Definition
- Exploration
- Drilling
- Construction
- Operation
- Decommissioning & Post-Closure

The classification scheme of geothermal projects, adopted by the CROWDTHERMAL consortium, is also presented.

The report reviews the environmental impacts of both deep and shallow geothermal systems, throughout the lifecycle of the project, while the criticality of each factor in terms of its impact on public acceptance is also discussed.

The literature review was based on existing studies on the environmental factors of geothermal energy systems, through a number of sources: project reports, scientific literature, online sources, books and other ongoing H2020 projects.

2 INTRODUCTION

This deliverable is part of Task 1.2 of the CROWDTHERMAL project. The aim of the task is to perform a review of environmental issues as factual and associated perceptions that operate as socio-environmental and psychological processes, influencing public support to geothermal energy. This deliverable documents the outcome of this review process.

This review has identified relevant sources from academic literature, ongoing and previous projects and industry and innovation reports aiming to synthesise an up-to-date critical evaluation of works performed to date with the view to inform on how environmental factors influence public support to the implementation of geothermal project.

This work builds on WP5 and D5.1 adopting the proposed classification of geothermal energy sources and project phases. The report is organised as follows. After this Introduction, the methodological framework of this review is presented, summarising the classification of technologies and the high-level categories of the environmental impacts. Sections 4-7 discuss in more detail the associated sub-risks, also discussing the relevance to the technology and the corresponding project phases mostly impacted. Section 8 comments on findings of this work through cumulative tables and critical discussions, summarising findings and dependencies of this work with other activities of the project.

3 METHODOLOGICAL FRAMEWORK OF REVIEW

3.1 CLASSIFICATION OF GEOTHERMAL ENERGY

Environmental impacts of geothermal energy vary depending on the employed technology. There are several types of geothermal energy technologies and different classification schemes. Figure 1 summarises the classifications adopted by the CROWDTHERMAL consortium and introduced in ANNEX I of the D5.1 Case Study Assessment Protocol. When classifying in terms of geothermal energy use, three main categories have been distinguished: thermo-electrical production, direct use (incl. combinations of electricity generation and direct use) and ground-sourced geothermal heat pumps.

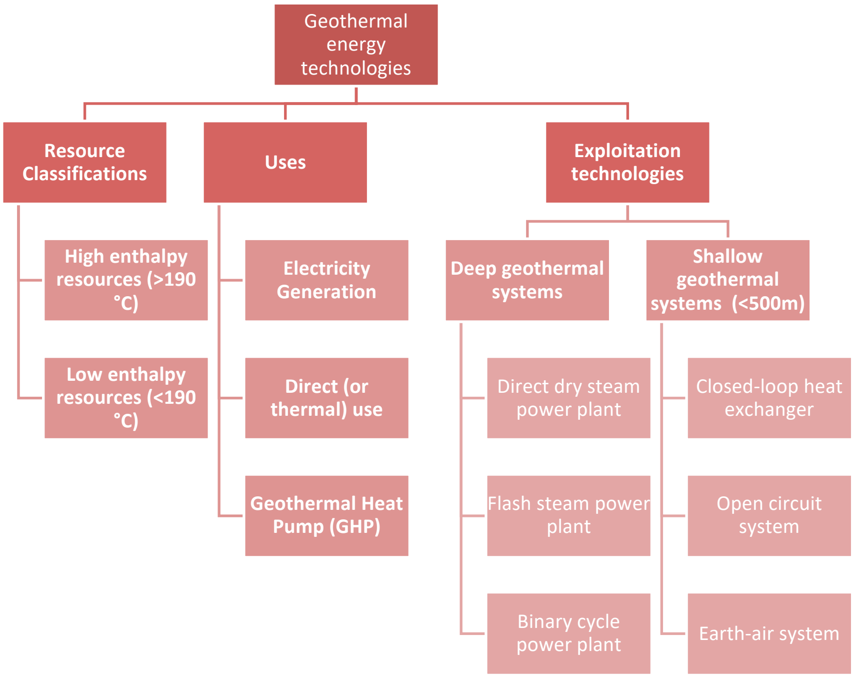

Figure 1: Classification of geothermal energy projects

Thermo-electrical production from geothermal energy is based on the deployment of a conventional steam turbine and electricity generator equipment. By drilling wells into the reservoir, hot liquid and steam from the production well enters the power plant and the steam is expanded powering the turbine to convert its energy into electricity through the generator. There are three types of exploitation technologies, depending on the reservoir's temperature, pressure and steam-to-liquid ratio: direct steam, flash steam and binary cycle power plants. These are typically deep geothermal systems (500m-5000m) and can either include a petro-thermal system or a hydro-thermal system. A petro-thermal system involves the performance of hydraulic stimulation, where water is injected into the subsurface under pressure to reactivate the naturally occurring fractures in rocks, like granite, with the view to increase the permeability of the reservoir and create an artificial subsurface heat exchanger (often referred to as Enhanced Geothermal System (EGS), although the term EGS can include non-petro-thermal systems) (Mannvit hf 2013; US Department of Energy 2004; Breede et al. 2013; Breede et al. 2015). Hydrothermal systems, on the other hand, rely on existing aquifers to pump hot geothermal fluid for electricity generation in the case of low-enthalpy resources, vs. self-flowing wells in high-enthalpy hydrothermal resources. Key elements across different exploitation technologies are summarised as follows:

- Direct dry steam: The conversion plant of this technology is a steam turbine engine that directly uses steam extracted from underground reservoirs. The steam, which has to be at least 99.995% dry to avoid scaling and erosion of the pipes and the turbine (DiPippo 2016), is directly piped to the power plant, turning the turbine and the generator. The steam is, accordingly, condensed and reinjected to the reservoir via another well. To date, direct dry steam plants are quite rare and favourable cases with typical examples Larderello in Italy and the Geysers in northern California. Typical sizes of direct dry steam plants range from 8-140 MW. A schematic representation of a direct dry steam power plant is illustrated in Figure 2. This is a very rare and favourable situation, as reported by (DiPippo 2016).

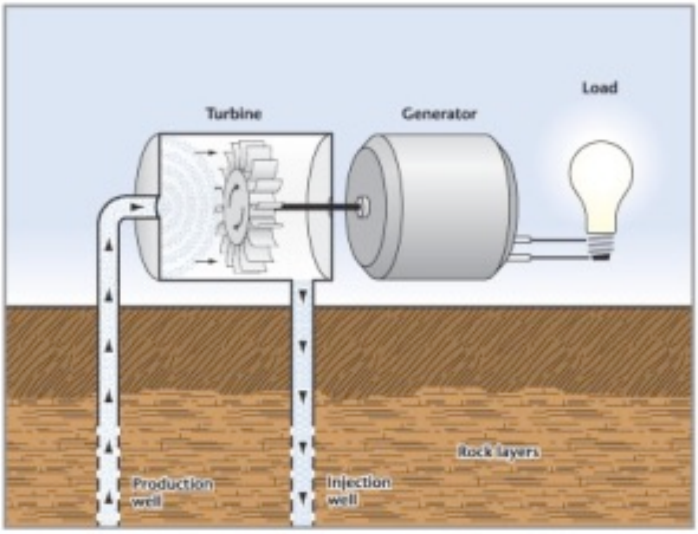

Figure 2: Direct steam power plant (Source: (US Department of Energy 2004))

- Flash-steam power plants are the most common type of geothermal plants in operation today and they involve the extraction of steam from the geothermal fluid following a separation process (flashing). The steam is subsequently directed to the steam turbine, which is connected to an electricity generator. The condensate is forwarded either for further flashing to lower pressures and temperatures, or reinjected into the underground reservoir. The reinjection has two advantages: (i) the reinjected liquid maintains the pressure in the reservoir and (ii) avoids land subsidence especially in the case of a shallow reservoir. Flash-steam power plants work best with high-enthalpy resources. The fluid fraction that exits the condenser is either reinjected, if not evaporated, through a wet cooling tower. Typical sizes of flash steam plants range from 0.2-150 MW plants according to the number of flashing processes. A schematic representation of a flash-steam power plant is illustrated in Figure 3.

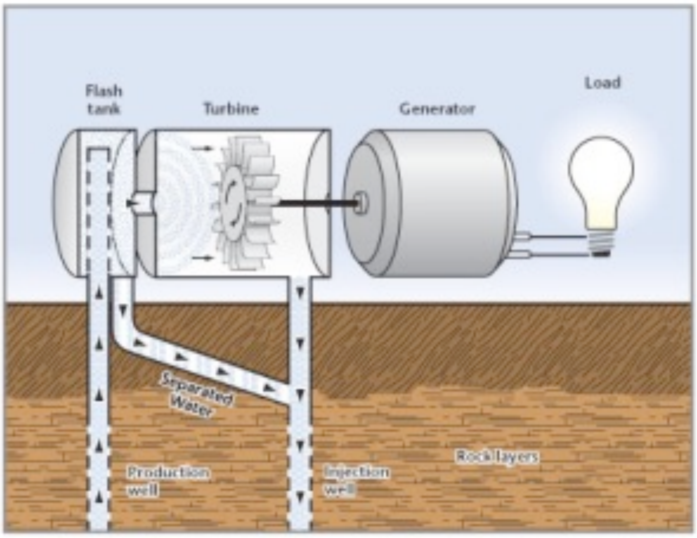

Figure 3: Flash-steam power plant (Source: (US Department of Energy 2004))

- Binary cycle power plants are usually appropriate for low and medium enthalpy geothermal fields, where the heat content of the geothermal fluid can be exploited to heat a working fluid via heat exchangers in a closed loop. The working (or else "binary") fluid is typically an organic compound (often isopentane) with a low boiling point (Mannvit hf 2013). Heat from the geothermal fluid (most existing binary plants recover heat of geothermal fluid in the range of 100–200°C (Tomarov and Shipkov 2017)) causes the working fluid to vapour and accordingly turns the turbines and in extension the generators. Binary power plants are closed-loop systems, mitigating drastically the emissions to the atmosphere. A schematic representation of a binary power plant is illustrated in Figure 4.

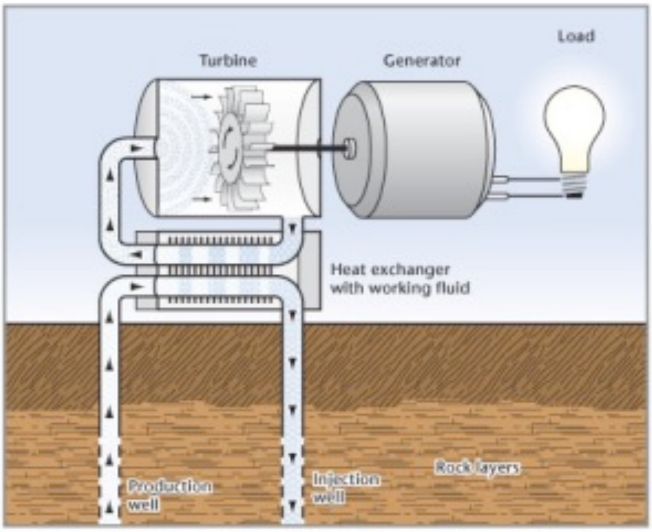

Figure 4: Binary power plant (Source: (US Department of Energy 2004))

Direct use of the geothermal resource comprises pumping hot water from the geothermal resource to provide heat for buildings, industrial applications, greenhouses, crop drying, ice melting, etc. This type of geothermal resource is called direct use, as the water stream brought up through the drilled geothermal reservoir and a mechanical system comprising piping, pumps, heat exchangers and control, deliver the heat directly to the end user.

Finally, the geothermal heat pumps (GHPs) utilise the constant temperature near the surface of the Earth to transfer heat from the ground during the winter and dispose heat for cooling during the summer. This type of geothermal technology typically uses shallow ground, which maintains a stable temperature (typically between 10°-16°C) as an energy storage device (Anderson and Rezaie 2019). In 2005, the installed thermal power for direct utilisation was 70 GW globally, with 55.2% using GHPs (Lund and Boyd 2016).

Apart from the power generation plants, there are also cases of low-temperature deep geothermal systems used for heating purposes (McCay, Feliks, and Roberts 2019). Those are the most abundant geothermal plants in Europe.

Characteristic types of shallow geothermal systems include:

- Closed-loop heat exchangers can provide heating/cooling and/or hot water in buildings (residences, schools, offices, etc.) and other applications (such as swimming pools, greenhouses, ice melting, etc.). These systems are also known as Ground Source Heat Pumps (GSHPs). There are two main geometrical configurations for closed-loop GSHPs: horizontal and vertical systems (Chaldezos and Karytsas 2017) (see Figure 5(a)-(b)).

- Open-loop systems use well or surface body water as the heat exchange fluid that circulates directly through the GSHP system. Once it has circulated through the heat exchanger coil system, the water returns to the ground through the reinjection well. This configuration is practical only if an adequate supply of relatively clean water is available. Open-loops are not as common as closed loops nowadays, not only as a result of the major improvements in closed systems up to date but also because of environmental concerns in some areas. Open-loop systems can also be applied if local codes and regulations regarding groundwater discharge are met, as open systems are often subject to local zoning laws and licensing requirements (Government of Canada 2017) (see Figure 5(c)).

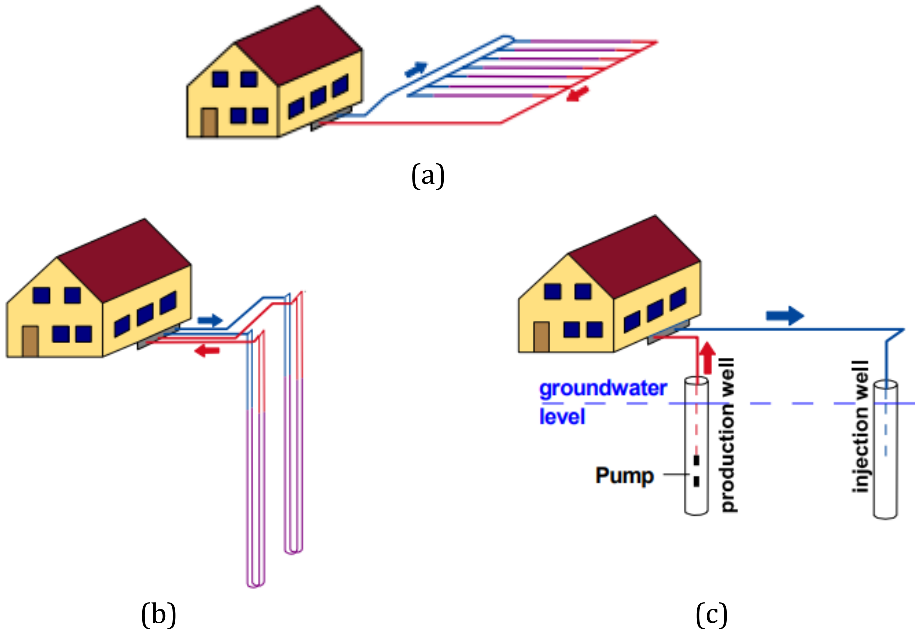

Figure 5: Geothermal Heat Pumps: (a) Closed-loop (horizontal), (b) Closed-loop (vertical) and (c) Open-loop system (groundwater well) (Source: (Sanner et al. 2011))

- Earth-Air Heat Exchanger (EAHE) systems can effectively be used to preheat the air in winter and precool it in summer. The temperature of earth at a depth of 1.5-2m remains fairly constant throughout the year (maintaining the earth's undisturbed temperature (EUT)), which is higher than ambient air temperature during the winter and lower during the summer. The system comprises a series of pipes buried underground at a particular depth, through which the fresh ambient air flows and gets cooled in summer (soil acting as heat sink) and heated in the winter (soil acting as heat source). The EAHE can effectively meet the heating/cooling requirements if the temperature of air at the outlet of the system is adequately low or high; otherwise, it can only reduce the heating/cooling load of the building through preconditioning the temperature (Bisoniya 2015; Bisoniya, Kumar, and Baredar 2014).

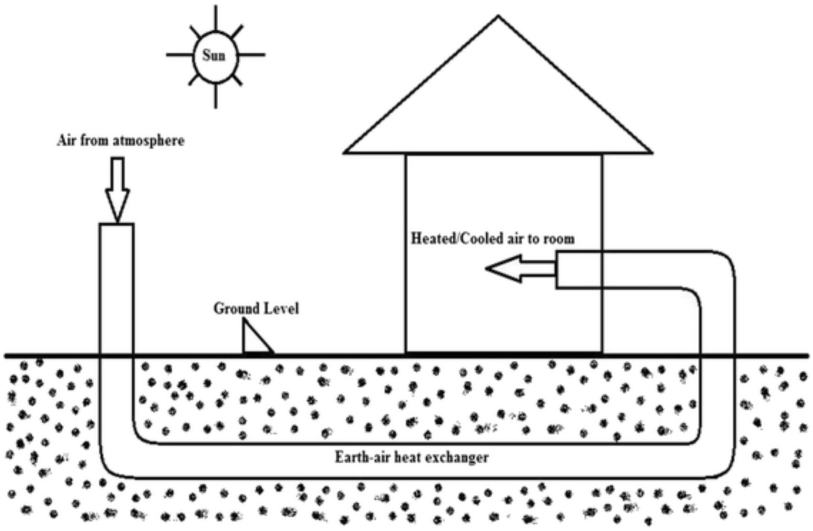

Figure 6: Earth-air exchanger system (Source: (Bisoniya 2015))

3.2 CLASSIFICATIONS OF PROJECT PHASES

The lifecycle of a geothermal energy project can be divided into the following stages (as introduced in ANNEX I of the CROWTHERMAL D5.1 Case Study Assessment Protocol):

- Project definition phase involves the literature survey of existing data and information from previous studies and an analysis of the conditions generally considered favourable for the presence of geothermal resources capable to develop into a commercially viable project. Furthermore, during this stage, the available geological maps and airborne data are examined, along with the identification of geophysical and geochemical sample sites. This stage is also usually associated with securing the exploration license.
- Exploration phase involves the acquisition of new geoscientific data (e.g. 3D seismic survey), integration of existing datasets with new ones, well path planning, transmission development and the process of securing drilling and testing permits (e.g. production well drilling permit) (GEA 2010; Serdjuk et al. 2013).
- Drilling phase includes the construction of the 1st full-size production/injection well, as well as subsequent resource development (i.e. the drilling of the second well in case of a doublet). The 1st well includes the construction of the drill pad, drilling and construction of the first well, production/injection test and fluid sample, as well as well stimulation in case of EGS. Resource development activities include drilling of a second well, doublet well testing / circulation test, drilling of any subsequent wells, as well as the acquisition of the plant construction permits.
- Construction phase involves building the actual geothermal plant, facilities (pipelines, electric power transformation and transmission lines) and wells, as well as testing it considering all health and safety aspects. In case of a district network, this stage involves the construction or extension of the project, if applicable. Additionally, during construction, the connection to the grid/heating network is realised, along with securing the operation permits.
- Operation phase comprises the commissioning and operation of the geothermal energy plant and the electricity generation/heating/cooling, its maintenance and monitoring.
- Decommissioning & post-closure activities are related to the field rehabilitation into its original status, site closure, well plugging and monitoring for potential releases from abandoned wells.

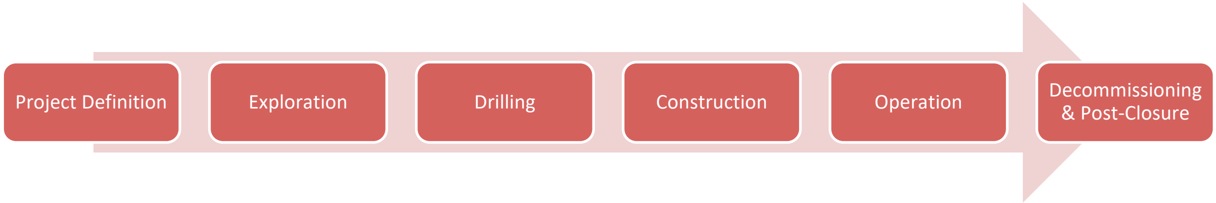

Figure 7: Representation of the lifecycle of a geothermal energy project

3.3 CLASSIFICATION OF ENVIRONMENTAL FACTORS

The development of geothermal projects is largely dependent on the issue of social acceptability by local communities of the potential environmental impacts of the implemented technology. Environmental effects vary depending on the geothermal energy system deployed.

In Europe, the status of geothermal utilisation and potential ranges from direct use of hydrothermal resources in sedimentary basins, to high-temperature geothermal potential found in volcanic areas. Sedimentary basins are present in multiple European countries, such as Germany, France (Paris Basin and Aquitaine Basin), Hungary (the Pannonian basin), Poland and Romania, while there is a lower number of European countries, characterized by young volcanic activity (mainly Iceland and Italy). Shallow and low-temperature deep geothermal is almost everyone available in Europe and is commonly harnessed through GSHP installations (Enex & Geysir Green Energy 2008). Share of installed capacity of shallow geothermal systems (mostly GSHP) amounts to 66.5%, direct use 26.2% and electricity 7.3% (Sanner 2019).

The majority of published work focuses on environmental concerns associated with deep high-temperature geothermal systems for power generation use (McCay et al. 2019). The technology required for these systems is more intrusive and implies extraction of geothermal fluids, which require a higher level of safety and environmental protection procedures (due to the chemical composition, temperature and pressure of the geo-fluids) (Manzella et al. 2018). However, it should be highlighted that the environmental effects of deep geothermal energy systems should be distinguished between high- and low-temperature prospects.

A number of environmental factors that have been reported for shallow geothermal systems in literature. Relevant factors include groundwater contamination due to leakages of contaminants in vertical closed loop systems, connection of different aquifers or connecting aquifers to the surface, flooding due to artesian groundwater conditions, ground uplift due to anhydrite-bearing formations, and thermal changes of soil and groundwater causing variations in the concentration of microbes (Zhu et al. 2017).

Various classification methods of environmental factors of geothermal energy plants exist in literature. This report will cover the various environmental effects focusing on the associated project phases and specific technologies. Figure 8 illustrates a schematic representation of the various implications of a geothermal power plant on the environment and Figure 9 shows the classification of environmental impacts followed in this report.

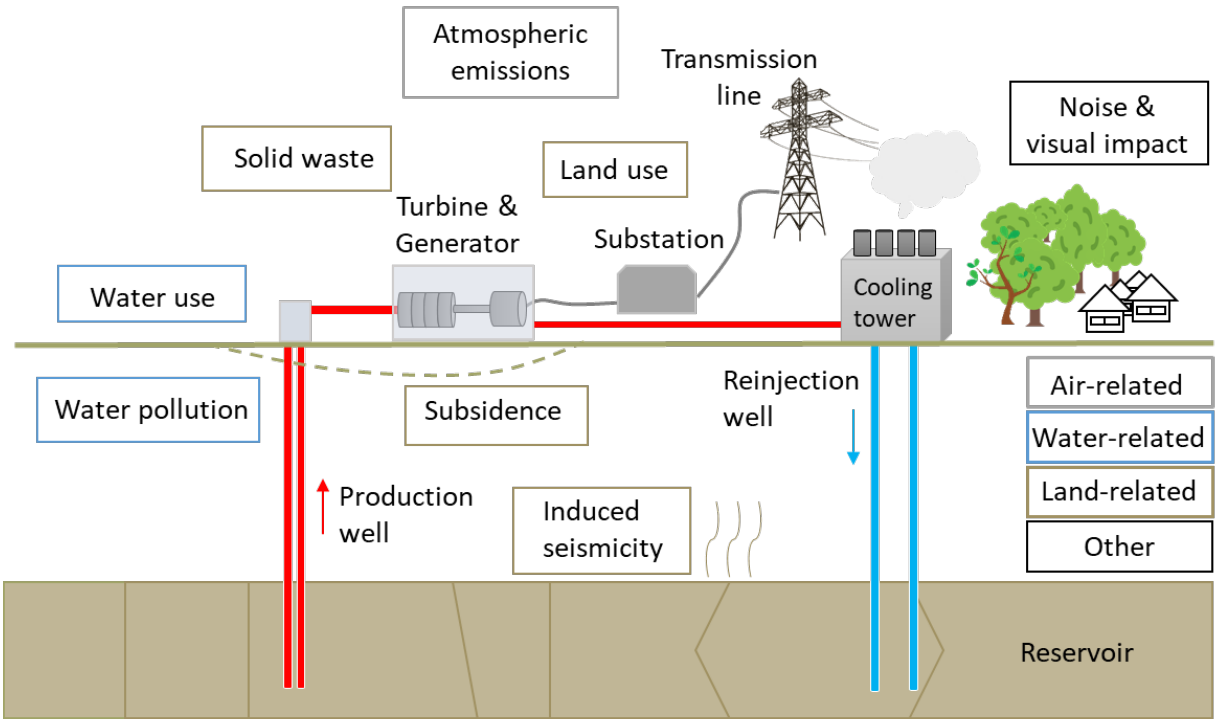

Figure 8: Representation of environmental impacts (partly adopted from (Bayer et al. 2013))

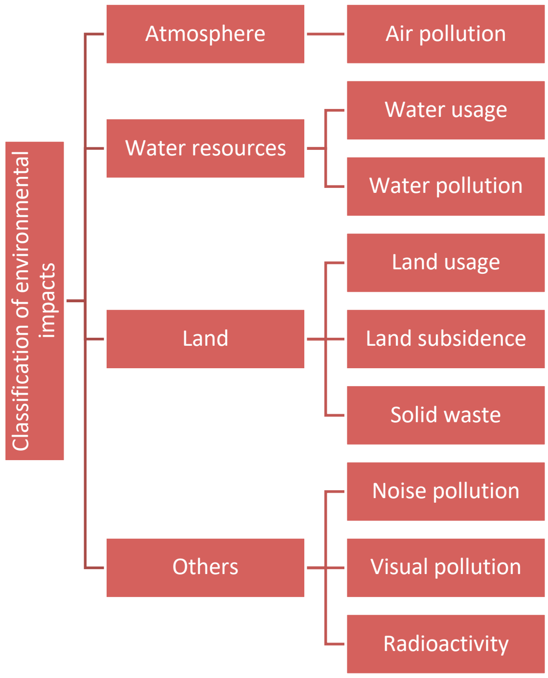

Figure 9: Classification of environmental impacts

4 ATMOSPHERE IMPACTS

4.1 AIR POLLUTION

4.1.1 Environmental impacts

Emission rates from geothermal energy plants are much lower than conventional fossil fuel-based energy plants, emitting about 5% of CO_2 (carbon dioxide), 1% of H_2S (hydrogen sulphide) and less than 1% of SO_x (sulphur oxides) than a coal-fired power plant of the same size, while certain types of geothermal energy plants produce close to zero emissions (Holm et al. 2012). Direct use geothermal heat produces only 7% of the emissions of gas-fired boilers (McCay et al. 2019).

High-temperature geothermal fluids in volcanic and magmatic areas and lower temperature geothermal fluids from sedimentary basins may contain non-condensable gases (NCGs), i.e. gases that do not condense at the same temperature and pressure as water, including mostly (95-99%) CO_2 with small amounts of NH_3 (ammonia), N_2 (nitrogen), CH_4 (methane), H_2S, etc. NCGs, in contrast to steam, are not able to condense at the turbine outlet of flash and dry-steam plants. The composition and gas content of geothermal fluids vary according to the geological formation of the reservoir, fluid temperature and depth (Manzella et al. 2019). For example, in low-temperature geothermal fluids of sedimentary basins, CH_4 or N_2 might be the dominating NCG (like in major parts of the Pannonian basin).Typical compositions of geothermal NCGs of high-temperature fluids are summarised in Table 1.

Table 1: Typical composition of Geothermal NCGs, weight % dry gas (Source: (Thráinn et al. 2016)**)**

	CO_2	H_2S	H_2	CH_4	NH_3	N_2	Ar
Median	95.4	3.0	0.012	0.15	0.29	0.84	0.02
Maximum	99.8	21.2	2.2	1.7	1.8	3.0	0.04
Minimum	75.7	0.1	0.001	0.0045	0.005	0.17	0.004

Release of gases in the atmosphere is a phenomenon called degassing and can occur during the geothermal development if the geothermal fluids extracted from the reservoir up to the surface have a gas content. For example, water which is the main constituent of geothermal fluids, in high enthalpy geothermal systems, can reach a temperature well above 100 °C; hence, when released in the atmosphere is in gaseous condition (water vapour in superheated conditions) (Manzella and Al. 2019).

- Carbon dioxide (CO_2) emissions

Carbon dioxide (CO_2) is the main NCG emitted throughout the life span of the geothermal power plant while its emission factors vary considerably. The reported direct carbon dioxide from geothermal power plants originally stems from degassing magma, and less frequently from decomposition of organic sediments (Ármannsson, Fridriksson, and Kristjánsson 2005). Bertani and Thain collected CO_2 emissions data from the 85% of geothermal power plants operating in 11 countries, in 2001 (Bertani and Thain 2002; Manzella et al. 2018). Results indicated a diverse range of values between 4-740 g/kWh, with a weighted average of 122 kg/MWh.

In some locations, such as the Mt. Amiata area in Italy, naturally high concentration of CO_2 (found in carbonates and phyllites) in the reservoir rocks and the shallow magmatic processes causes high emissions of this compound from the soil, thermal and volcanic manifestations (Manzella et al. 2018; Tassi et al. 2009). As emissions of CO_2 can naturally occur in geothermal regions, special interest lies on the change of CO_2 emissions to the atmosphere after the geothermal energy utilisation and stimulation. Bertani and Thain observed a decrease in natural CO_2 emissions in Larderello during the operation of the power plant. On the other hand, geothermal power plants in Iceland were found to contribute 8–16% to the national CO_2 emissions in the year 2002 (Ármannsson et al. 2005).

- Hydrogen sulphide (H_2S) emissions

Hydrogen sulphide (H_2S) is the most abundant NCG released from a geothermal well after CO_2 in case of high-temperature resources. This compound is often subject to local environmental concerns, because of its smell and toxicity; however, odour nuisances appear early before toxic concentrations. Values reported in literature range between 0.5-6.4 g/kWh (Hunt 2000); as an example, the 213MW Hellisheidi power plant was reported to emit 6.96g/kWh of H_2S to the atmosphere. Deployment of abatement technologies, however, have significantly decreased total emissions by about an order of magnitude (Bertani 2012). H_2S is the pollutant which is generally considered to be of greatest concern to the geothermal community due to its effect on the general public. This can be mitigated through public awareness and maintaining good relations with the local community (Mannvit hf 2013).

- Ammonia, Boron, Arsenic and Mercury emissions

Ammonia, boron, arsenic, and mercury emissions in the atmosphere can be leached by rain and become a hazard to soil and surface water located close to the power plant. An average value of 0.06 g/kWh has been reported for NH_3 by (Bloomfield et al. 2003) from high-temperature geothermal power plants. When oxidized, ammonia contributes to soil acidification (Manzella et al. 2018).

Boron can be found as boric acid in the drift emitted from the cooling towers of high-temperature geothermal plants, which when combined with ammonia, it forms ammonium borate, which tends to deposit on the plant's walls. Boric acid can also be found in evaporitic deposits from hydrothermal water as salt (Manzella et al. 2018). It is a critical compound in various locations like Larderello (Italy) and Kizildere (Turkey) (Arnórsson 2004).

Arsenic is a substance of high toxicity, which is usually emitted during volcanic eruptions. If present in geothermal fluids, arsenic remains in aqueous phase and can be easily reinjected to the reservoir. Emissions of arsenic may occur, usually in low concentrations, through the drift in cooling towers.

In certain cases, mercury concentrations in vegetation, fish, surface waters, and the atmosphere in proximity to high-temperature geothermal plants, have been traced (Arnórsson 2004; Bacci et al. 2000); as for example in Larderello (up to 1.8 mg/g in mosses within a distance of 0.6 km).

- Methane (CH_4) emissions and other compounds

Additional gases emitted from high-temperature geothermal facilities include methane and nitrogen oxide (NOx) but in substantially lower amounts (Mannvit hf 2013).

Methane is found at low concentrations in geothermal steam, but due to its significant global warming potential (GWP), its containment is important. Reported methane annual emissions factors are derived from the New Zealand geothermal electricity production (0.85 g/kW) and the weighted average for all geothermal power plants in the USA 0.75 g/kW (Bloomfield et al. 2003).

Nitrogen oxide (NOx) and particulate matter emissions are generally present in minor concentrations.

In general, EU and national regulations exist that establish air quality standards for dangerous substances, such as mercury and arsenic. In the absence of regulatory standards for other contaminants, reference values established by international organisations (e.g. WHO) or other authorities in this field (e.g. American Conference of Governmental Industrial Hygienists ACGIH) are typically taken as good practice by regional authorities.

4.1.2 Relevant project phases and geothermal technology types

The amount of direct emissions of a geothermal system depends not only on the geological profile of the reservoir, but also the geothermal technology employed, the project phase, life cycle and the application of additional abatement systems, cooling and reinjection technologies (Bayer et al. 2013).

Direct emissions can occur during multiple project phases including drilling, construction, operation and decommissioning. Degassing, which is most common during the drilling and production phases, can also occur during testing and after well abandonment, in case the well has not been correctly sealed (Manzella and Al. 2019). Furthermore, fugitive emissions can occur during the plant commissioning and operation. The composition of released mixture also varies substantially across the different high-temperature locations, geological characteristics and even during the lifetime of a power plant. As such, during production, emissions of H_2S increase more than CO_2 emissions, while during operation, a steam cap may evolve below the surface and temporally release high gaseous concentrations. Emission factors presented in literature are mixed, including measured and indirectly calculated amounts with various underlying assumptions. During the operation of the plants, a gradual decline in NCG concentration in the reservoir fluid can be observed, leading to gradually decreasing gas emissions, which is largely a result of reinjection of geothermal brine with low NCG concentration into the reservoir (Thráinn et al. 2016).

As afore-mentioned pollutants are mainly found in geothermal fluids in underground reservoirs deeper than 500m, shallow geothermal systems and closed loop systems, as for example pumped binary technology, are not expected to induce a major environmental impact on the atmosphere. However, binary systems do use a low-boiling working fluid, e.g. isopentane with a GWP= 11, which, similar to the working fluid of low-enthalpy GHPs, may escape in low quantities over time (Bayer et al. 2013). In flash and dry steam plants, the NCGs are usually released together with the water vapour at the downstream of the condenser and at the outlet of the cooling towers, which can be wet cooling systems (Manzella 2019; Mannvit hf 2013). Abatement equipment is used to capture and reinject dangerous compounds, during the operation of geothermal plants especially in case of flash and dry-steam technologies (Manzella and Al. 2019), such as mercury and hydrogen sulphide with a capturing rate of 94.7% and 98.9%, respectively. Drift eliminators may also be deployed in the cooling towers to capture the condensed fluids from the emitted drift (which includes boric acid and arsenic) (Mannvit hf 2013).

The emission intensity of direct heat deep geothermal projects will inevitably vary according to the borehole depth, heat capacity, and pipeline length and geology of the reservoir. A recent study has estimated a carbon intensity in the range of 9.7–14.0 kg $CO_{2,eq}$/MWh, which is over an order of magnitude less than natural gas-fired boilers (McCay et al. 2019).

5 WATER IMPACTS

5.1 WATER USAGE

5.1.1 Environmental impacts

Geothermal power plants can require a considerable amount of water throughout the various phases of the asset life, depending on the size of the plant, the technology type, the working temperatures and the cooling mechanism (Bayer et al. 2013).

Spent geothermal fluid is not usually fresh water used as drinking water or for agriculture (Bayer et al. 2013). In high-enthalpy projects, blowdown losses and losses from the evaporation of geo-fluid and steam during, for example flashing and cooling, are often replaced by make-up water added to the reinjected steam condensate. This is the case in wells such as The Geysers, Darajat and Larderello. Make-up water does not need to be freshwater, however, the lower the quality of the injected water, the more frequent the cycling required and thus the larger the quantity.

Water consumption during operation of the plant is determined by the cooling technology, which majorly depends on the geofluid/steam inlet and outlet temperature. Water is also consumed to minimize scaling and manage dissolved solids. Geothermal fluids extraction rates of flash steam power plants has been estimated 15-27m^3/MWh (Clark et al. 2010).

5.1.2 Relevant project phases and geothermal technology types

Large quantities of water are required mainly during the drilling phase (up to 1000 m^3/d) to produce mud and cement and during the operation phase to supply the cooling tower and to minimize scaling. Total water consumption for 1 m well construction has been estimated around 5–30 m^3, depending on geology, technology, number of liners and depth. As such, a 2 km well would require around 8,000–55,000 m^3 of water. The use of engines requiring the use of water are not specific to geothermal operations and can be encountered in many diverse industries (Bayer et al. 2013; Manzella et al. 2018; Tomasini-Montenegro et al. 2017).

The amount of water consumption is also dependent on the type of the system and the cooling technology. There are conflicting findings from literature comparing water consumptions during the operation phase of different geothermal power plants (Macknick et al. 2011). Typically, binary power plants use a small amount of water for the air-cooling method, while the water-cooling method which is less often applied, has a higher water intensity, and constitutes a key issue when freshwater from rivers or aquifers is extracted. However, the water-cooling method for the geothermal power technologies is, in general, less water-demanding than alternative power plants, such as nuclear or fossil fuel based power plants. Another reference suggests that high-temperature geothermal power plants need more "water" than conventional steam plants, taking into consideration the lower conversion efficiency (8–15%) (Fthenakis and Kim 2010).

Flash-steam power plants cool the outlet steam to liquid state before reinjecting it to the reservoir. A part of the geothermal fluid (about 15–20%) is likely to be released as water vapour into the atmosphere after flashing to steam and evaporate from cooling towers or holding ponds. However, this does not induce a major impact if no additional freshwater is needed as balance.

The usage of shallow geothermal systems can potentially entail the risk of flooding of adjacent buildings and infrastructure due to artesian groundwater conditions released once the shallow wells have reached the groundwater level. In 2009, drilling activities for a geothermal energy application in the city of Wiesbaden resulted in the eruption of a 7-m-high groundwater spring when the depth of the borehole reached 130 m after hitting an artesian aquifer, causing estimated damages of 500,000 EUR (Fleuchaus and Blum 2017). Flow from artesian aquifers can be controlled inside the well through applying appropriate hydraulic isolation to avoid flooding and depletion of the aquifer.

5.2 WATER POLLUTION

5.2.1 Environmental impacts

Contaminants relevant to water pollution are similar to those of atmospheric pollution (hydrogen sulphide, boron, ammonia, mercury, arsenic, lead, cadmium, iron, zinc), with a diverse composition of high-temperature geothermal fluids, depending on the geological setting of the system. The production mode, time and technology also impact on water pollution risk. For technical and economic reasons, it may not always be possible to reinject all of the geothermal fluid extracted from high-enthalpy resources. Local environmental concerns have been raised regarding the insufficient control of discharged geothermal fluids that contain some harmful compounds, such as Hg and As. For low-temperature fluids, one of the major contaminants is salt (NaCl). However, environmental standards and limits are set to control the deheated fluid.

There is also risk of contamination of water aquifers by the reinjection of geothermal fluids, as well as the drilling of fluids and infiltration in case of well casing failure. Furthermore, gullying can occur by waste fluids during drilling and testing, causing contamination of freshwater depending on the composition of the fluid (Bayer et al. 2013). The well is likely to intersect one or multiple aquifers of different quality to reach the resource, divided by impermeable levels. In order to avoid the accidental connection of aquifers via the wellbore, or the fluid intrusion to non-targeted aquifers, proper mitigation measures, during drilling, and operation of a geothermal plant should be introduced. The interconnection of aquifers can occur as a result of the difference in hydraulic pressures between aquifers. There are various reasons for the above phenomenon to happen, including failures due to poor cementation, mechanical damage from well construction, thermal stresses and failure or degradation of materials, corrosion and scaling, blowouts throughout the life cycle of operations and improper reinjection applications. Thermal changes may be caused by the production from geothermal reservoirs and the reinjection of fluids tens of degrees cooler than the reservoir's (Manzella and Al. 2019).

Groundwater contamination can also happen in geothermal heating applications, as a result of temperature changes which can affect the properties of the subsurface and the growth rates of microbes, especially to shallow geothermal plants. The use of GSHP systems induces local temperature changes in the ground and consequently the water evaporation, dissolved oxygen and chemical reactions, affecting the microbes present in soil and the ecological balance. Increasing the soil temperature leads to a drop in the solubility of oxygen, which affects the absorbing capacity and consequently the growth of plants. On the other hand, the decrease in underground temperature (when GSHP is mainly used for heating) can impede the growth or even cause death of certain kinds of plants and microbes. In frigid zones, the rise of underground temperature might also result in subsidence and release of N_2O and CH_4 (Zhu et al. 2017).

Surface water protection management includes infrastructure to prevent leakage of geothermal fluid to environment, which is also controlled by inspection of geothermal pipes and the corrosion monitoring system. Corrosion monitoring can take place through testing on metal coupons or corrosion probes with electrodes. Apart from the corrosion monitoring, there is a calendar-based inspection of geothermal pipes to check the wall thickness of the pipes at hotspots and representative points of the system. A water management system can also assist in the separation of rainwater, geothermal fluid and waste water of the high-temperature geothermal plant. During the commissioning and the cleaning phase, a quantity of geothermal fluid can be discharged out of the closed geothermal loop. The mix of water and geothermal fluid is collected by a waterproof system and reinjected in the reservoir, while the rainwater is collected in a tank by gravity (Ravier et al. 2016).

5.2.2 Relevant project phases and geothermal technology types

Blowouts are rare incidents which include the uncontrolled flows of formation fluid from drilled wells due to, most frequently, natural causes, for example, drilling over a high pressure zone (Manzella and Al. 2019). Blow-out-preventers (BOPs) are used to prevent the occurrence of blowouts.

Stimulation of EGS has been associated with public concerns that components of fracturing fluids can present a threat to drinking water resources. However, operators argue that EGS projects mostly inject fresh water and rarely use additives and chemicals in the fracturing fluids (e.g. tracers, proppants and diverters) to re-open faults through dilatant shearing of natural fractures to increase the permeability of the reservoir. Additionally, when additives are necessary, non-toxic substances are selected (Breede et al. 2013). For binary geothermal plants, leaks from the circuit of working fluids may be toxic or explosive. The risk of groundwater contamination is minimised if the reservoir recedes beyond the reach of the groundwater aquifers. Furthermore, wells casing is necessary to comply with environmental requirements and ensure the integrity of geothermal wells (Mannvit hf 2013).

Key environmental groundwater effects of shallow geothermal systems include risks associated with the leakage of anti-freeze or refrigerant present in the heat carrier fluid (allowing contaminants to enter the groundwater), the connection of different aquifers or connecting aquifers to surface, the drilling into artesian aquifers, the drop of groundwater level in karst areas including the drying out of natural springs and thermal effects (Sanner et al. 2011). In closed-loop GSHPs, the heat carrier fluid must be selected so that the groundwater contamination in case of leakage is minimised, hence it should be non-toxic and biodegradable. Pure water is an ideal heat carrier from a thermodynamic and environmental point of view; however, as in most central and northern European countries, winter design temperatures are below 0°C, an antifreeze should be added to achieve lower freezing points (Emmi et al. 2017; Sanner et al. 2011). Potential leakage of the water-antifreeze compounds to aquifers could cause serious contamination. To address this, biodegradable and low toxicity anti-freeze additives such as propylene glycol are preferred, while some local regulations have forbidden anti-freeze additives for Borehole Heat Exchangers (BHE) (Casasso and Sethi 2019). Other dangerous additives include corrosion inhibitors or biocides (Klotzbücher et al. 2007). Furthermore, drilling of shallow geothermal plants should not result to the connection of aquifers to the surface, nor between aquifers of different depths, causing changes in the hydraulic, geophysical and geochemical parameters of separate aquifers. These phenomena are usually prevented by grouting the BHEs or cementing the annulus. In case of open-loop systems, there is risk of possible mobilisation of contaminants from nearby waste deposits (or contaminated sites, such as industrial areas and/or landfills) due to the fluctuating groundwater level.

Karst areas are characterised by the existence of carbonate rocks. Due to heterogeneity of carbonate rock aquifers, there is significant exploration risk as geothermal drillings may miss high-permeability zones. In case of connecting hydraulic permeable cavities, there is a risk of dropping the groundwater level, leading to the drying out of natural springs or contamination resulting from groundwater mixing. To address this effect, backfilling of cavities with larger amounts of grouting are usually needed (CRETA 2018).

Finally, changes of groundwater temperature can potentially influence the physical and chemical properties of the subsurface and the concentration and growth rates of microbes (Haehnlein, Bayer, and Blum 2010). In general, aquifers have a long memory, and therefore the long term effects of GSHP systems have to be carefully considered both during the summer and winter to estimate how the change in groundwater temperature affects the degradation of chemicals in groundwater and the growth rate of microbes (Zhu et al. 2017).

6 LAND IMPACTS

6.1 LAND USAGE

6.1.1 Environmental impacts

Land used by geothermal plants includes the area occupied by the drilling pads (often temporary), the well-heads, the geothermal plant facilities, the geothermal fluid transport pipelines and the electricity transmission lines (in case of a power plant). In low-temperature projects, the two wells of the doublet are typically drilled from one drilling pad.

Land surface is used during the different project phases of a geothermal power plant; this may be temporal (during construction and reclamation) or permanent (operation) and include use of land, changes to landscape and to natural features. Permanent land used is smaller than the temporal land use. The Bureau of Land Management (BLM) estimates an average value of "land disturbance" of 0.85 km^2 during the construction of a high-temperature geothermal power plant of 50MW (BLM 2008). Larderello, with 22 dry-steam power plants and total installed capacity of 595 MW, has an exploited land area that covers 250 km^2. Without taking into consideration wells and transmission lines, reported land use values amount to 1.2–2.7 m^2/MW, while with wells the amount of land is estimated 2.3–9.7 m^2/MW for different sites, technologies and plant capacities (Bayer et al. 2013).

Special care should be taken for surface manifestations of geothermal processes or discharges (hot/steaming ground, hot springs, mud pools, geysers, etc.), which are often fragile and vulnerable to large-scale and enduring extraction of geofluids (DiPippo 2016). For example, extensive geothermal developments in New Zealand, in combination with other factors, have resulted in the disappearance of more than 100 geysers (used as tourist attractions with hot springs, mud pools, and steaming ground) while recovery does not appear to be possible (Glover, Hunt, and Severne 2000). Geyser basins are usually located on the banks of rivers where groundwater emerges to the surface as springs. There was a declining trend of chloride concentration and reduction in flow of Geyser Valley springs at Wairakei New Zealand, which was correlated with the volume of fluid extracted from the geothermal power plant reservoir. As a response to this, reinjection wells were drilled, while the Government of New Zealand ordered the closure of the geothermal wells within 1.5 km of Pohutu Geyser (Barrick 2007). Nowadays, special attention is given to such sensitive areas for the protection of these geologic features and lessons have been learnt on well placement optimisation vis-à-vis ground water level. However, this demonstrates that the total impact on land is not limited to the surface occupied by the power plant and facilities.

6.1.2 Relevant project phases and geothermal technology types

High capacity flash-steam plants have usually lower land footprints per MW than small-size binary power plants with cooling towers at high-temperature sites. Land use data of various types of high-temperature geothermal plants are summarised in Table 2.

Land disturbances occur throughout the whole service life of the asset. During plant construction and equipment installation, the land required for a high enthalpy power plant (like the Hellisheidi power plant in Iceland) and the required equipment/facilities, is approximately 5 hectares. Following decommissioning of the plant, the amount of land is likely not to be recoverable in its original form (Mannvit hf 2013). During well drilling, drilling pads for deep geothermal projects typically require a total area of 4,000–5,000 m^2, to allow the manoeuvring of the drilling rig and storing drill pipe, casing, and other equipment (Agemar et al. 2014). (Mannvit hf 2013) reports that the occupation of land for the well pads and the possibly affected area ranges from 1-1.5 hectare/well. When multiple doublet wells are installed through different pads, surface disturbance from installation of reinjection pipelines prior the long-term well testing cannot be avoided, it can nonetheless be reduced via cautious landscaping upon completion of the work and by avoiding ecologically delicate zones. Drilling numerous (for example, 2-4) deviated wells from the same pad obviously minimizes land disturbances of the geothermal plant. In general, the amount of required land for the construction of a geothermal plant is comparatively smaller than other renewable energy plants. As estimated by (Arent et al. 2014) under specific assumptions, in a study on environmental implications of high renewable electricity penetration in the U.S., mean land use factor of geothermal energy amounts to 500 MW/km^2, wind onshore 5 MW/km^2 and solar PV 50 MW/km^2.

Table 2: Land use for different types of geothermal energy plants (Source: (Goldstein et al. 2012))

Geothermal energy plant	Land use (·1000 m^2) per installed MW
110-MW flash plant, excluding wells	1.3
20 MW binary, excluding wells	1.4
49 MW flash-rankine, e.g. Salton Sea Calif., excluding wells	2.3
Single-flash plant, excluding wells	1.2
56 MW flash, including wells, pipes	7.5

6.2 INDUCED SEISMICITY

6.2.1 Environmental impacts

Geothermal activities are concentrated into natural seismic active zones. Geothermal energy production is related to extensive extraction or circulation of geofluids, and manipulation of the shallow and deep ground, which can lead to environmental effects, such as induced seismicity (Bayer et al. 2013; Evans et al. 2012). Geothermal activity tends to change the characteristics of a reservoir by extracting and injecting hot and cold fluid, respectively. Water circulation can perturbate the initial hydraulic and thermal equilibrium in the subsurface, leading to some seismic activity. The rates of injection, pressure difference, temperature difference, fluid volumes and injection duration are all relevant factors affecting the risk of a seismic event. Although micro seismicity (i.e. seismometer-detectable seismic events with a magnitude below 2-3) is often associated to geothermal development, few geothermal projects have induced seismic events perceivable by the population (Bayer et al. 2013). If the geothermal area is remote, there is little public anxiety associated with the induced seismicity. In some sites, however, which are in proximity to urban areas, sensed seismicity may not be perceived as an isolated annoyance, but rather, it could raise concerns about the cumulative effects of repeated small events and the possibility of future larger earthquakes (Majer 2006). An indicative example is the Pohang EGS project, which was suspended after the Mw 5.5 earthquake in 2017 and was formally ceased in April 2019 (DESTRESS 2018). Similarly, in December 2006, during the hydraulic stimulation of a geothermal project in the city of Basel, more than 10500 seismic events were detected by a six-sensor borehole array, installed at depths between 300 and 2700 meters around the well. Slight nonstructural damage was claimed by the local homeowners with a damage sum US$7 million (Kraft et al. 2009).

6.2.2 Relevant project phases and geothermal technology types

As with all environmental impacts, induced seismicity is associated with specific types of technology. Induced seismicity more typically happens during well drilling, stimulation and testing of deep geothermal resources (typically more than 3-5 km deep). Major induced seismicity occurs during the hydraulic stimulation of petro-thermal EGS, as well as at the beginning of the water circulation. During hydraulic stimulation, freshwater is injected under high pressure into the well causing shear displacement of the faults/fractures of the reservoir and enhancing its permeability. At the beginning of the utilisation, the pressure usually drops abruptly and subsequently the change in pressure declines until it reaches a balance when the injection of fluids is equivalent to the recharge of the reservoir. During normal operation, the enhanced permeability should be sufficient for comparably low injection pressures of the de-heated fluid (Manzella and Al. 2019).

To manage this risk, the Owner of a geothermal energy plant project should implement risk prevention strategies, e.g. the Protocol for Induced Seismicity Associated with Geothermal Systems, which includes the evaluation of applicable laws and governing regulations, the installation of a microseismic monitoring network and the use of a traffic light system (Mannvit hf 2013).

6.3 LAND SUBSIDENCE & DEFORMATION

6.3.1 Environmental impacts

Land subsidence can occur when fluid and steam from geothermal reservoirs is removed, causing the sinking of the geothermal reservoir and potential damages to the built environment in the surrounding area (Cook et al. 2017). Geothermal plants are commonly built in steep, volcanic terrains, where slumps and landslides are likely to occur, leading to occasionally severe incidents and damages to buildings, as well as human fatalities. A characteristic example comprises the landslide occurring at the Zunil I geothermal field in Guatemala in 1991, killing 23 people (Flynn et al. 1991).

Subsidence is more common in liquid dominated fields. The subsidence rate at Wairakei geothermal field (New Zealand) has reached a maximum of 48 cm/year during the mid-1970s (Allis 2000), at Larderello (Italy) 25 cm/year, and at Svartsengi (Iceland) 1 cm/year. Change in the regional water and heat flows can also induce landslides.

6.3.2 Relevant project phases and geothermal technology types

Subsidence is likely to occur during well drilling and testing, construction and early operation of deep geothermal projects, while the extraction of geofluid exceeds the inflow (natural or through

reinjection) into the reservoir. During the early reservoir depletion stage and early operation of the well, reservoir pressure and temperature may drop with the removal of geothermal fluid from the ground, causing ground deformations, and change in contour and in regional hydrological flow regime. Conversely, reinjection of geothermal fluids can generate surface tensile fractures and fissures to the surface (Bayer et al. 2013; Rissmann et al. 2012) and develop new paths for the circulation of gas and water (Bayer et al. 2013). The pressure increase within the geothermal reservoir can result in a ground uplift, which can be partially addressed by the contraction of rocks and sediment resulting from the temperature drop (Manzella and Al. 2019).
Vertical GSHP systems may also be responsible for land deformations. The land uplift of the community Staufen, Germany occurred by the swelling of water-free anhydrite during the transformation to water-bearing gypsum once the shallow boreholes provided pathways for the surficial groundwater to reach the anhydrite-bearing sediment in the subsurface (anhydrite recrystallizes as gypsum when interacting with water). Significant structural damages to buildings (higher than 50 million EUR) were caused as a result of the swellable anhydrite formation as well as due to artesian groundwater and two interacting karst formations. Main reason was deemed to be faults during the well drilling stage, as the borehole were not properly cemented and backfilled for the last meters of the well due to cave-ins, creating flow paths for the groundwater to ascend through the fracture system into the anhydrite zones. Such occurrences are rare and can be prevented by applying proper sealing of the boreholes (Figure **10**), through a cement based backfill, which can be thermally enhanced to reduce the negative impact on the BHE performance (CRETA 2018; Sass and Burbaum 2010).

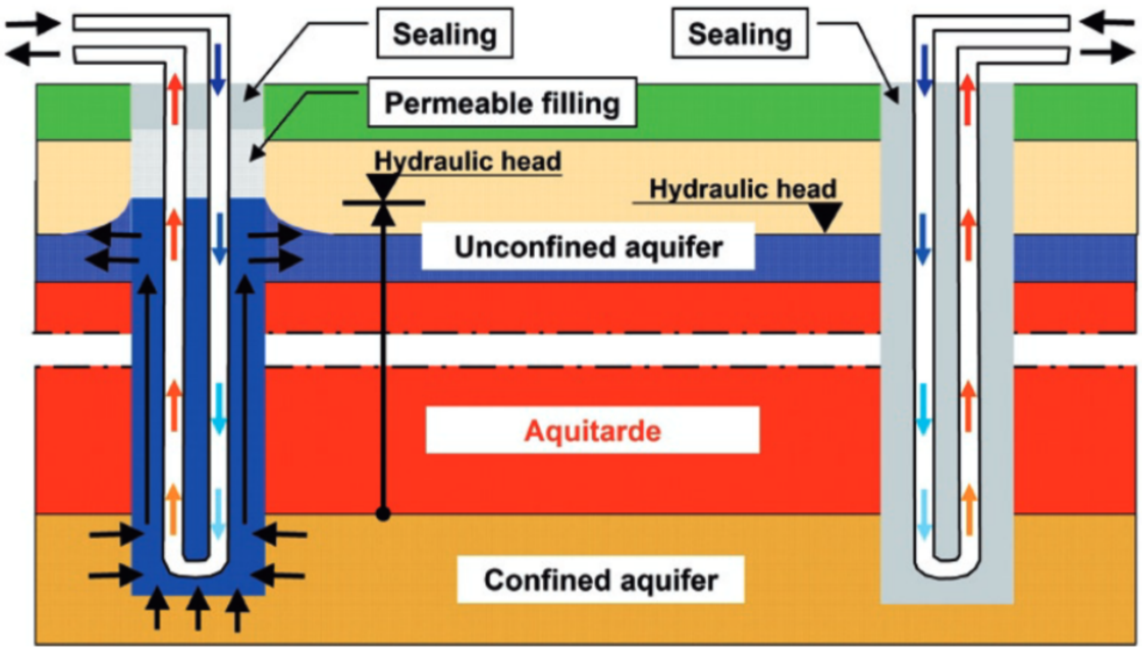

Figure 10: Unsealed (left) versus unsealed (right) BHEs (Source: (Sass and Burbaum 2010))

6.4 SOLID WASTE

6.4.1 Environmental impacts

Solid waste from geothermal energy systems depend on the reservoir temperature and fluid composition, the types of brine treatment facilities and the field operating conditions. Typical waste of low temperature geothermal systems include cuttings and residues produced during drilling, steel, copper, scrap metals, excavated soil, as well as plastics from packaging, construction material for buildings and road construction (Manzella and Al. 2019). In high temperature geothermal systems, scale from cooling water, scale from maintenance, toxic metals and hazardous waste from geothermal fluids in pipes, vessels filters and other tools can also be found (Vetter 1983).

6.4.2 Relevant project phases and geothermal technology types

Solid waste from geothermal energy production can be created during the drilling and operation phases. Common drilling waste includes cuttings, cement deposits and mud. Additional waste materials from geothermal activity comprise deposits, activated carbon from abatement systems, as well as residues resulting from chemical deposition in pipes and vessels (containing As and heavy metals) and deposits in cooling towers (with potential accumulation of Hg). Towards the end of the well repair and drilling activities, it is a standard process to blow (or air lift) the well for a period of time to clean it from cuttings, acid or other residues produced during chemical well stimulation (Mannvit hf 2013). Chemical stimulation involves the injection of chemical additives into the geothermal target formation, dissolving certain minerals and increasing the hydraulic pathways in the rock to enhance its permeability.

During the geothermal energy production (power or direct use), extraction of metals and minerals from geofluids, as by-products can be a profitable activity; however, this is highly dependent on the primary mineral concentrations in the geothermal fluids. The mineral resources to be extracted with greatest economic potential are lithium, zinc and precious metals such as gold, platinum and silver. Removal of silica is of indirect value, as it leads to a lower achievable reinjection temperature and associated higher electricity generation in case of high-temperature (steam) power plants.

A summary of known geothermal by-product recovery projects has been conducted by (Clark et al. 2010), indicating that in the past, several substances (such as boric acid, sulfur, potassium and ammonium salts) were recovered from geothermal energy plants until they lost economic competitiveness to other mining processes. One of the most metal-rich geothermal location can be found near the Salton Sea in the Imperial Valley of southern California, USA, where geothermal fluids have a high zinc content, which has been mined for a short period of time, until the process appeared to be unprofitable (Bayer et al. 2013)

During construction of the geothermal system, major source of solid waste includes the waste produced by the contractor, who is obligated to dispose it to an approved waste dump as prescribed in the health, safety and environment (HSE) management program of the project (Mannvit hf 2013).

During power plant commissioning and operation, the usual method for scaling mitigation in high-temperature systems (pipes, vessels and mechanical equipment) is the addition of chemical inhibitors into the geofluid. The introduction of the inhibitor could potentially cause some environmental risks to the geological environment although currently new biodegradable inhibitors have been developed; alternatively, a thermodynamic scaling control system can be employed, as a more environmentally friendly solution against scaling. In case of a low-temperature deep geothermal system, the fluid is usually reinjected into the 3-5 km depth.

7 NOISE, VISUAL POLLUTION AND RADIOACTIVITY

7.1 NOISE POLLUTION

7.1.1 Environmental impacts

Throughout the life of a geothermal energy system, noise can be created during the well testing, drilling and building activities, operation and decommissioning.

Impacts of raised noise levels may include temporary nuisance to visitors and tourists visiting the area, principally during the drilling and testing phase of the project (2-6 months for high enthalpy and around 2 months for medium enthalpy systems) (Mannvit hf 2013).

7.1.2 Relevant project phases and geothermal technology types

Noise level originating from drilling is of the order of 80 to 120 dB covering a radius of 100m (muted around 85 dB). Although this noise level is not dangerous to health, hearing protective equipment should be used by professionals working in the site, while in case a residential area is in proximity, noise barriers need to be installed along with additional sound barriers, like trees planted at strategic locations. During well testing, noise levels resulting from the release of high pressure steam through a silencer is between 70–110 dB. The cumulative noise impact depends on the total number of wells being tested. The noise level of plant construction and equipment installation is a standard, temporary, construction noise (from drill rigs, concrete mixers, cranes and various lifting equipment) and does not exceed 80 dB (Mannvit hf 2013).

The noise level during the plant commissioning and operation of binary plants are generally somewhat higher than in flash steam power plants (around 85-90 dB). The risk of serious noise impacts from geothermal power facilities is rather small. Sound insulation on the machines emitting high level of noise and the plant control room (where operators are located) is a common reasonably effective and financially viable countermeasure (Mannvit hf 2013).

During the operation of the plant, main sources of noise include the operation of cooling towers, transformer and power station. Typically, water-cooled towers are larger than air-cooled condensers and emit higher noise levels (Bayer et al. 2013).

Demolition noise is mostly caused by construction vehicles namely bulldozers, cranes trucks, and graders during the plant dismantling (Kristmannsdóttir and Ármannsson 2003).

7.2 VISUAL POLLUTION

7.2.1 Environmental impacts

Surface disturbances of geothermal plants are associated with landscape effects (such as deforestation), land occupation (as discussed above), as well as disturbances associated with road traffic and dust emissions (Manzella and Al. 2019).

Visual changes to the landscape as a consequence of geothermal activities are regarded as a key factor in areas of touristic and cultural interest or in residential sites, as it can destroy locations of important scenic value (Kristmannsdóttir and Ármannsson 2003).

7.2.2 Relevant project phases and geothermal technology types

Visual impacts occur during the whole lifecycle of the geothermal energy plant. During the drilling phase, the potential visual impact is associated with the installation of tall drill rigs, wellheads and pipelines (Mannvit hf 2013). To address this issue, wellhead can be enclosed in a well house, which also provides security for the equipment.

Following the drilling phase, only a small pump house and the injection pipeline remain visible, which (if not situated in a rocky landscape) can be hidden under the ground to minimise visual impact. The injection pipeline is commonly slightly elevated, a few cm above the ground and in case pipes cross the constructed roads, they are positioned inside an appropriate channel (Mannvit hf 2013).

During the plant construction and equipment installation of a geothermal power plant, the envisaged (electrical and control) equipment is housed within the power plants, However, in case of suitable climate, heat exchangers can be situated outside of the housing. Furthermore, there is usually an air- or water- cooled tower for cooling the working fluid and the substation that connects the plant with the grid, which is situated close to the rest of the equipment. Visual impact of buildings and rest of the equipment can be managed through careful layout and orientation of the buildings and landscaping.

During operation, the installed infrastructure, i.e. the plant facility and pipelines, can be painted to blend with the background (DiPippo 2016). Furthermore, the plant structures should be located as close to the wells as possible to minimize the visual impact of the whole facility. However, the size of the plants built today is much smaller and compact than the massive models built in the early days (Bayer et al. 2013). On the other hand, visual impact of shallow and low-temperature deep geothermal plants (such as district heating systems and GSHPs) is minor and these facilities are easily integrated into communities.

7.3 RADIOACTIVITY

7.3.1 Environmental impacts

As the geothermal fluid flows through a fractured granite, naturally enriched in radionuclides such as uranium and thorium, a small fraction is leached by the fluid and can reach the surface. Although the natural radioactivity of geothermal fluid is low and does not surpass significantly the ambient radioactivity, well drilling cuttings and the development of scale within the casing and surface equipment can significantly increase the fraction of radionuclides and subsequently the occurrence of radioactivity contamination (Manzella and Al. 2019; Ravier et al. 2016).

Radioactive tracers have been used to perform doublet well testing. Reinjection of the geofluid assists in maintaining the reservoir pressure, but it can lead to premature thermal breakthrough that can degrade the quality of reservoir operation (Li, Shiozawa, and McClure 2016). Doublet well testing aims to ensure that this hazard is minimal during the operating life of the doublet. The most relevant process to assess the likely occurrence of thermal breakthrough is the use of tracer testing techniques through the introduction of tracer chemicals into the reinjected fluid to measure the time that it takes for the tracer to get to the production well. The test can yield important data on well permeability, as well as the degree of thermal breakthrough risk. In previous years, radioactive tracers have been used to conduct the testing, however despite their effectiveness, they are not recommended nowadays due to their toxicity. Fluorescent substances have been used as tracers, such as fluorescein in Iceland. Other fluorescent tracers that have been used include rhodamine water tracer, naphthalein sulphonates and potassium iodide; compounds which are not listed as toxic or damaging (Rosea et al. 2001).

To mitigate this hazard, geothermal operations involving radioactive materials must comply with the European and national regulations, imposing thresholds on radioactive limits (Mannvit hf 2013; Manzella and Al. 2019).

7.3.2 Relevant project phases and geothermal technology types

Radioactivity of deep geothermal energy (such as EGS) originates from the underground radionuclides leached by the geofluid, which is extracted from the ground (e.g. granite). Radioactivity contamination depends on the technology employed (closed-loop systems are expected to have a minimal radioactivity impact) and can typically be observed during well drilling, testing and operation. Unlike nuclear plants, geothermal wells do not produce any dangerous radioactive by-products; however, regular monitoring is necessary to ensure radioactivity levels do not surpass the safe limits.
In the Upper Rhine Graben, Germany, there is a comparably high potential for radioactive scales, which would precipitate within the heat exchanger and would have to be regularly removed and disposed as radioactive waste. However, an inhibitor is added to keep the radioactive nuclides in solution, which can be reinjected into the same reservoir depth (almost 4 km) where the fluid has been produced.

8 DISCUSSION AND CONCLUSIONS

Geothermal energy is an environmentally friendly, renewable and sustainable form of energy. One of the main barriers to geothermal development is social acceptability and perceived environmental factors have been cited as one of the critical reasons affecting public acceptance of the technology (Reith et al. 2013). This report provides a state-of-the-art review on the environmental issues associated with geothermal energy, influencing public support on the development and deployment of the technology.

In Europe, the share of installed capacity of shallow geothermal systems (mostly GSHP) amounts to 66.5%, direct use 26.2% and electricity 7.3% (Sanner 2019). Hydrothermal resources in sedimentary basins are present in multiple European countries, such as Germany, France, Hungary, Poland and Romania. Shallow and low-temperature deep geothermal potential is almost everyone available in Europe, as opposed to high-enthalpy deep geothermal potential, which can be found in only a few European countries, characterized by young volcanic activity (mainly Iceland and Italy).

An overview of environmental issues throughout the project lifecycle of deep and shallow geothermal plants is presented in Table 3, along with relevant mitigation measures. The Table focuses on drilling, construction, operation, and decommissioning & post-closure phases of the geothermal energy project, where the most critical environmental impacts were detected, according to the results of the review.

Although the majority of literature focuses on environmental factors induced by high-temperature deep geothermal power plants, shallow (e.g. GSHP systems) and low-temperature deep geothermal energy is also subject to environmental concerns.

A number of environmental effects has been identified for shallow geothermal systems in literature. These are mainly associated with the risk of groundwater contamination, land subsidence and deformation, and visual/noise pollution. As far as groundwater contamination is concerned, this can be potentially a result of leakage of additives (i.e. anti-freeze compounds for BHEs) and other compounds to aquifers, the hydraulic connection of originally separated aquifers or connection of aquifers to the surface, as well as the concentration of bacteria due to the temperature change of the soil. In case of open-loop systems, there is risk of possible cross-contamination from nearby waste deposits due to the fluctuating groundwater level. Public may perceive groundwater contamination as a major environmental impact, especially when groundwater sources are used to provide drinking water. In the past, significant structural damages to buildings have occurred as a result of land deformations such as the land uplift due to the swellable anhydrite formation (e.g. in the city Staufen), as well as the flooding of adjacent buildings and infrastructure due to artesian aquifer released once production wells reached the groundwater level. Furthermore, shallow geothermal projects can be responsible for land subsidence due to errors during drilling and grouting. Visual and noise pollution are of minor significance, while the performance of environment impact assessment is not generally mandatory depending on the shallow geothermal energy system (Gil and Moreno 2020). Relevant mitigation measures are in place to manage above environmental risks, a number of which are summarised in Table 3.

GHG emissions of geothermal power plants vary according to the power plant type and the natural composition of the reservoir. Drilling of production and injection wells, along with the construction activities of geothermal power systems demonstrate a high contribution to the environmental impacts (Martín-Gamboa et al. 2015). The degassing and blow-out phenomena, which may occur during the drilling and construction phases of deep geothermal high-temperature systems can lead to the release of NCGs (CO_2, H_2S, NH_3, etc.) to the atmosphere. Although geothermal power plants emit substantially less GHGs than fossil power plants, the fact that a renewable power plant may not be GHG-neutral during its development and operation could trigger social resistance. Results from a survey on public acceptability of geothermal systems suggested that people would prefer geothermal projects to be installed at least 100 km away from their community. As such, community engagement would be important for technologies that need to be in proximity to the end-use application, such as in direct-use projects (Reith et al. 2013).

Induced seismicity, land subsidence and resulting damages have been detected as among the major negative acceptance factors for deep geothermal systems, following a series of seismic events and landslides causing severe damages (Majer et al. 2007; Reith et al. 2013). Public concerns on induced seismicity vary depending on the project and public engagement (Trutnevyte and Wiemer 2017). Results from a study on public acceptability indicated that human-induced earthquakes may be perceived more negatively than naturally occurring ones, even if the damage is equivalent; at the same time, the public acceptability of induced earthquakes increases, when people affected by the earthquake, participated in the decision making process prior to implementing the technology (McComas et al. 2016). It was highlighted that apart from the geological characteristics of the site, the type of technology plays an important role on the total environmental impact of the geothermal systems. Flash power plants have comparatively higher environmental impact due to the flash processes of geothermal fluids (Liu and Ramirez 2017), while in closed-loop technologies, such as binary systems, the impact was deemed to be lower. During the drilling and construction phases, intense visual impact due to the existence of the drilling platform, surrounding equipment, etc., as well as increased noise levels, is a considerable social acceptance issue for affected citizens.

For more detailed analysis on the factors affecting public acceptance of geothermal development, the reader should refer to Deliverable D1.1 of the CROWDTHERMAL Project "International review of public perception studies".

Table 3: Overview of environmental issues throughout the project life of deep and shallow geothermal plants

Type	Impact	Drilling	Construction	Operation	Decommissioning & Post-Closure	Mitigation measures
Deep geothermal systems*	Atmosphere	- Degassing of water vapour and NCGs during drilling and production tests - Blow-outs from drilling through an over-pressure zone - Release of geofluid spray that could damage vegetation of surroundings	- Degassing of water vapour and NCGs during plant construction - Fugitive emissions of geofluids	- Fugitive emissions from open systems (mainly dry and flash steam plants) - Leakage of inflammable and poisonous (when in high concentration) organic working fluid in binary plants	- Degassing in case the well has not been correctly sealed - Chemical pollution when binary power plant is emptied of its working fluid (and risk to egress into the ground).	- Geothermal plant should be designed to avoid any steam releases to the atmosphere and NCGs should be treated at the cooling tower (Mannvit hf 2013).
	Water	- Water use during well drilling - Injection of large amounts of water under pressure for hydraulic stimulation (EGS)	- Water use for concrete production	- Water use for the water/air-cooling tower - Release/evaporation of water vapour from cooling towers or holding ponds (flash-steam) - Groundwater contamination from geofluids - Make-up water requirements	- Risk associated with ground water contamination due to corrosion of the wells (resulting in leakage of hot fluid to the surface and to the groundwater).	- Installation of wells casing to prevent the groundwater contamination.
	Land	- Induced seismicity from well stimulation - Land subsidence from extraction of geo fluids - Land use for well pads and plant facilities	- Land use for installation of the geothermal plant	- Impacts on land from geothermal energy utilisation (e.g. disappearance of geysers) - Induced seismicity from the injection of geothermal fluids - Land subsidence - Land occupation from complete installation	-	- Project Owner to implement the Protocol for Induced Seismicity Associated with Geothermal Systems

Type	Impact	Drilling	Construction	Operation	Decommissioning & Post-Closure	Mitigation measures
	Solid waste	- Production of drilling mud	- Normal construction waste (lubricant spill, cleaning fluid waste, metallic waste, packing, cement, etc.) - Blowing/ air pumping of the well to clean it from cuttings, or other remains	- Hazardous solid waste produced by scaling in the system	- Disposal of surplus chemical inhibitors, tracer materials, etc.	- Selection of contractor(s) with good environmental record - State in contract requirements on special waste ponds - Consider thermodynamic scaling control rather than inhibitors to minimize hazardous substances in the geothermal fluid
	Noise, visual pollution and radioactivity	- High noise levels (80-120 dB within a 100 m radius) - Geothermal fluid enriched in radionuclides (mainly in EGSs) can reach the surface - Visual intrusion (e.g. from installation of tall drill rigs) - Radioactive scales which would precipitate within the heat exchange	- Temporary typical construction noise (<80 dB)	- Visual impact during operation (following the commissioning of the plant only a small pump house and the injection pipeline remain) - Noise from cooling towers and generator	- Permanent visual impacts from surface disruptions	- Careful sitting of the plant to avoid ecologically and historically sensitive areas - Minimize surface disturbance and visual impact during construction - Careful landscaping during operation. - Application of sound barriers, such as plantation of trees at adjacent locations. - Ear protective equipment for the workers - Use of inhibitors to keep the radioactive nuclides in solution

Type	Impact	Drilling	Construction	Operation	Decommissioning & Post-Closure	Mitigation measures
Shallow geothermal systems	Atmosphere	- Fugitive emissions	- Fugitive emissions	- Fugitive emissions	-	
	Water	- Connection of different aquifer layers or connecting aquifers to surface - Drilling into artesian water leading to flooding of buildings and infrastructure - Swellable anhydrite formation	- Water use for concrete production	- Risk from potential leakage of antifreeze and other compounds could cause groundwater contamination - Changes of soil temperature leading to concentration of microbes to ground water resources	- Corrosion may damage the wells and allow leakage of pollutants into the groundwater	- Grouting the Borehole Heat Exchangers (BHE) or sealing the annulus - Legal constraints on the installation of geothermal systems (especially open loop) in water protection areas for drinking waters
	Land	- Land subsidence from drilling and grouting of BHE. - Land use during the drilling process - Uplift of the ground surface due to swelling processes	- Land clearance and use	- GHP system leads to local temperature changes in the ground affecting the ecological balance	-	- Proper sealing of the boreholes, through a cement based backfill
	Solid waste	- Well drilling mud and cuttings	- Normal contractor's construction waste	- Solid waste, resulting from operation and maintenance of the plant, as well as urban waste from the personnel	- Waste materials can be surplus chemical inhibitors, tracer materials, chemical reagents	- Important to select only contractor(s) that have good environmental record. State in contract requirements on special waste ponds

Type	Impact	Drilling	Construction	Operation	Decommissioning & Post-Closure	Mitigation measures
	Noise, visual pollution and radioactivity	- Noise from well drilling and visual pollution	- Temporary standard construction noise	- Minor visual pollution	-	- Application of hearing protection for the workers - Noise barriers to avoid disturbances of residential areas - Minimize surface disturbance and visual impact during construction - Careful landscaping during operation - Avoiding ecologically sensitive areas where possible

*Environmental effects principally refer to high-enthalpy deep geothermal systems.

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